REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-

0556

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		01 APRIL 98 - 31 MARCH 01

4. TITLE AND SUBTITLE
Development and Verification of Experimental Databases for Pancakes Structures in Geophysical Flows

5. FUNDING NUMBERS
F49620-98-1-0364

6. AUTHOR(S)
Basil Nicolaenko

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Mathematics
Arizona State University
Tempe, AZ 85287-1804

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NM
801 N. Randolph Street Room 732
Arlington, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-01-1-0024

11. SUPPLEMENTARY NOTES

20011126 106

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This research program aims toward investigating optical turbulence in stably stratified fluids. Optical turbulence arises during the propagation of electromagnetic waves through a random medium enduring refractive-index fluctuations, and is characterized by phase modulations (scattering) at wave fronts and diffraction-generated wave intensity fluctuations along the beam path. Electromagnetic transmissions in the atmosphere, such as the propagation of laser-beams or microwaves, are severely distorted by optical turbulence. Distortion is most profound in regions with high density gradients (stratification) and turbulence, such as the lower stratosphere and upper troposphere. Although the dynamics of stratified turbulence has been extensively studied in relation to such middle-atmospheric flows, very little attention has been paid to the properties of concomitant optical turbulence. On the contrary, optical turbulence in isotropic turbulent flows has been extensively studied, but the practical utility of such studies to atmospheric electromagnetic transmissions is severely limited due to the strong anisotropy of stratified turbulence. This research addresses a number of key issues on optical turbulence in stratified turbulent flows by employing laboratory experiments and associated theoretical/numerical analysis. The proposed work is expected to contribute significantly to the USAF efforts to develop prediction schemes for laser-beam propagation in middle atmospheric layers via its Airborne Laser (ABL) Program.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	9
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

Development and Verification of Experimental Databases for Pancakes Structures in Geophysical Flows

Final Report (6/30/01)
AFOSR Grant F49620-98-0364
(AASERT Grant)

Alex Mahalov and Basil Nicolaenko
Department of Mathematics
Arizona State University
Tempe, AZ 85287-1804
alex@taylor.la.asu.edu
byn@stokes.la.asu.edu

H. J. S. Fernando
Center for Environmental Fluid Dynamics and
Department of Mechanical and Aerospace Engineering
Arizona State University
Tempe, AZ 85287-6106
j.fernando@asu.edu

ARIZONA STATE UNIVERSITY
OFFICE FOR RESEARCH & SPONSORED PROJECTS ADMINISTRATION
MAIN CAMPUS
PO BOX 873503
TEMPE, AZ 85287-3503
(480) 965-5479
FACSIMILE
(480) 965-2455

October 9, 2001

Wendy M. Veon
Administrative Contracting Officer
Department of the Air Force
801 N. Randolph Street, Room 732
Arlington, VA 22203-1977

Subject: F49620-98-1-0364 (ASU TKA 6125/TE)

Dear Mr. Veon:

Attached is the Final Technical Report for Dr. Nicolaenko's referenced grant which was listed on the AFOSR delinquency reported dated September 28, 2001.

I am the single point of contact for delinquent reports. Contct me if you need additional information. I can be reached by phone at (480) 965-2179, fax (480) 965-8013 or e-mail at debra.barnes@asu.edu.

Sincerely,

DMurphy
Debra Murphy, CRA
Manager, Sponsored Relations and Compliance

jm

Enclosures

1. Objectives

This research program aims toward investigating optical turbulence in stably stratified fluids. Optical turbulence arises during the propagation of electromagnetic waves through a random medium enduring refractive-index fluctuations, and is characterized by phase modulations (scattering) at wave fronts and diffraction-generated wave intensity fluctuations along the beam path. Electromagnetic transmissions in the atmosphere, such as the propagation of laser-beams or microwaves, are severely distorted by optical turbulence. Distortion is most profound in regions with high density gradients (stratification) and turbulence, such as the lower stratosphere and upper troposphere. Although the dynamics of stratified turbulence has been extensively studied in relation to such middle-atmospheric flows, very little attention has been paid to the properties of concomitant optical turbulence. On the contrary, optical turbulence in isotropic turbulent flows has been extensively studied, but the practical utility of such studies to atmospheric electromagnetic transmissions is severely limited due to the strong anisotropy of stratified turbulence. This research addresses a number of key issues on optical turbulence in stratified turbulent flows by employing laboratory experiments and associated theoretical/numerical analysis. The proposed work is expected to contribute significantly to the USAF efforts to develop prediction schemes for laser-beam propagation in middle atmospheric layers via its Airborne Laser (ABL) Program.

2. Final Progress Report

This project was focused on the evolution of stratified turbulent regions and their contribution to density fluctuations in stratified fluids with the hope of understanding optical turbulence in the middle atmosphere. To this end, in the first part of the study, we considered the most simple case of stratified turbulence, namely a single turbulent patch. This patch was created by sustained oscillations of a monoplanar grid in a salinity stratified fluid (as the molecular diffusivity is unimportant at high Reynolds number conditions, salinity stratified experiments carried out in water were expected to give the same results as temperature stratified experiments in air). The flow configuration is shown in Figure 1 and preliminary observations related to such experiments are shown in Figures 2. The nature of turbulence is such an isolated patch was studied by DeSilva & Fernando (1998) who clearly demonstrated how the patch first grow vertically by the engulfment of non-turbulent fluid by the turbulent eddies and how the vertical growth is arrested by the stratification at the Ozmidov length scale $L_o = (\varepsilon_0 / N^3)^{1/2}$ or at the buoyancy length scale $L_b = \sigma_w / N$. Hereε_0 is the turbulent kinetic energy dissipation, N is the buoyancy frequency and σ_w is the r.m.s. vertical velocity. Thenceforward, the patch collapses, forming intrusions that propagate sideways as a result of horizontal pressure gradients developed due to mixing within the patch. Strong refractive index gradients exist at the upper and lower edges of the patch as well as at the frontal zone of the intrusion. A laser beam was transmitted through the turbulent patch and light scattering by the patch boundaries were recorded. Figure 3 shows the appearance of the turbulent patch on a shadowgraph (the light intensity variation over which is determined by the second derivative of density; Boyer et al. 1989) and the appearance of the laser beam on a video detector after passing through the patch. The initial diameter of the laser beam was 0.5 cm and its intensity fluctuates rapidly upon passing through the turbulent patch.

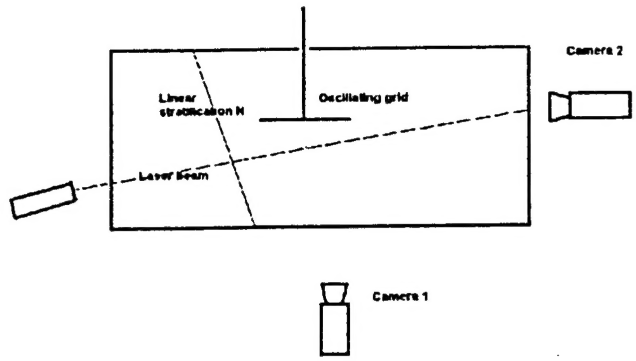

Figure 1: The experimental apparatus that was used to produce a shear-free turbulent patch in a density stratified fluid.

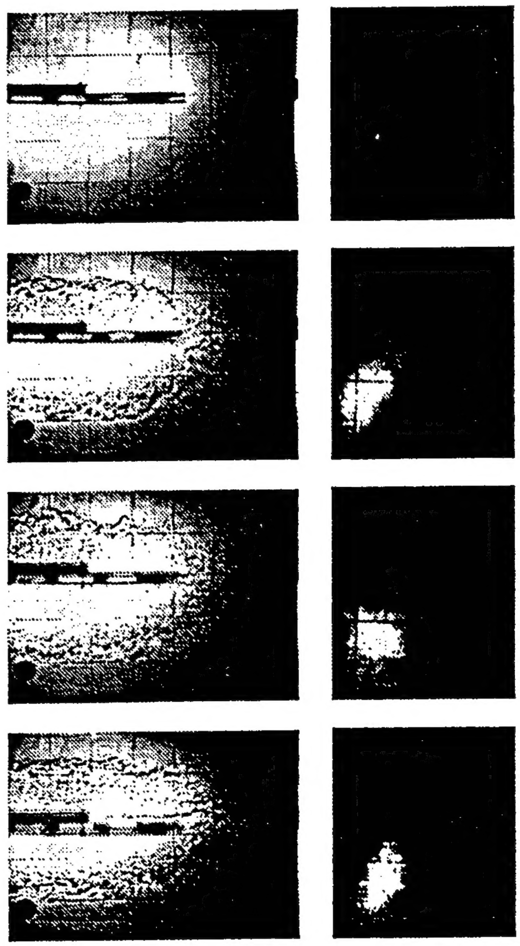

Figure 2 The time evolution of the turbulent patch obtained by shadowgraph technique (which illustrates refractive index variations) and recorded by the camera 1 (Fig. 1). The corresponding images of the laser spot, produced by the beam traversing the turbulent patch, recorded by camera 2 (Fig. 1), are also shown.

In the experiments, we observed the growth of the patch in the vertical direction, the collapse of the patch to form intrusions and the propagation of the intrusion. The turbulence within the patch was measured by suspending neutrally buoyant particles in the patch and by using particle-tracking velocimetry (PTV). The signatures of the laser beam arriving through the patch was recorded on a digital camera as shown in Figure 2. Probability density function of the centroid of this laser patch is shown in figure 3.

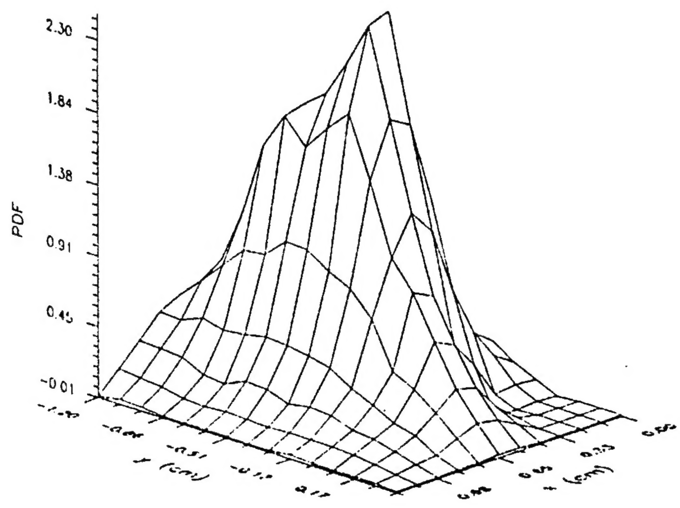

Figure 3: Probability density function of position of the centroid of the laser light patch intensity.

Identical experiments were conducted in a rotating reference frame with the aim of characterizing spectral properties of turbulence within the patch. The evolution of the turbulent patch is sketched in figure 4 for different backgrounds. (i) homogeneous fluid without background rotation, (ii) stratified fluid without background rotation and (iii) stratified fluid with background rotation. Figure 5 shows a sequence of images obtained in experiments for the rotating and non-rotating cases. Dimensionless vertical and horizontal scales of the patch are presented as functions of dimensionless time in figure 6. Figures 7 and 8 show horizontal and vertical velocity spectra for the cases with and without background rotation.

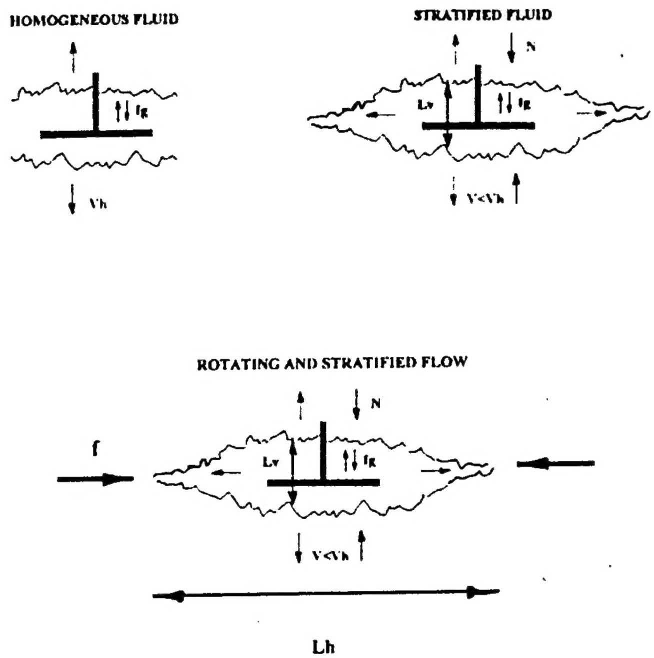

Figure 4. A sketch depicting evolution of turbulent patch.

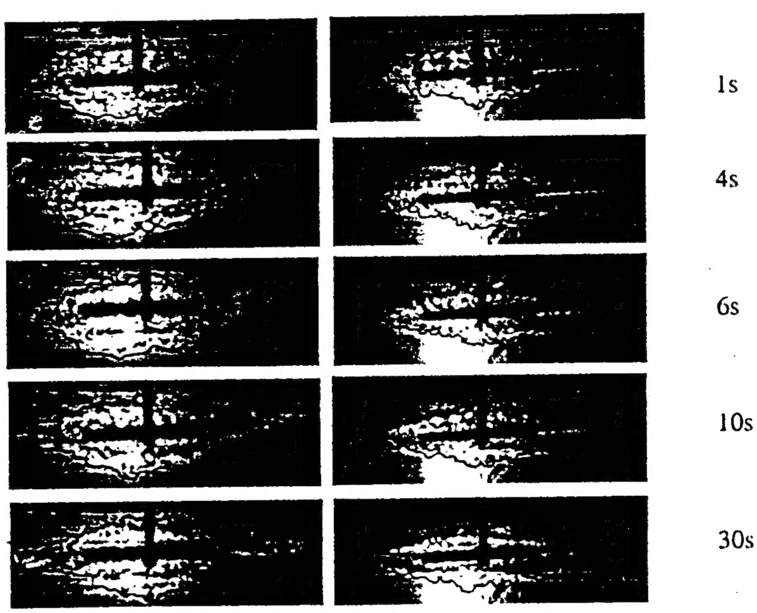

Figure 5. Sequence of images showing the evolution of a turbulent patch without background rotation (left) and with background rotation (right). Note the retardation of lateral spreading.

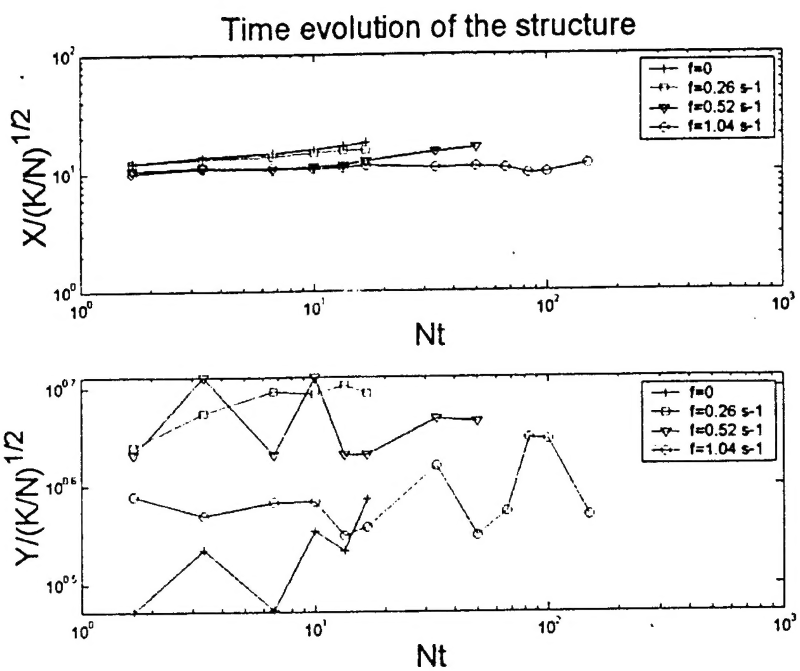

Figure 6. Dimensionless horizontal and vertical scales of the patch versus time.

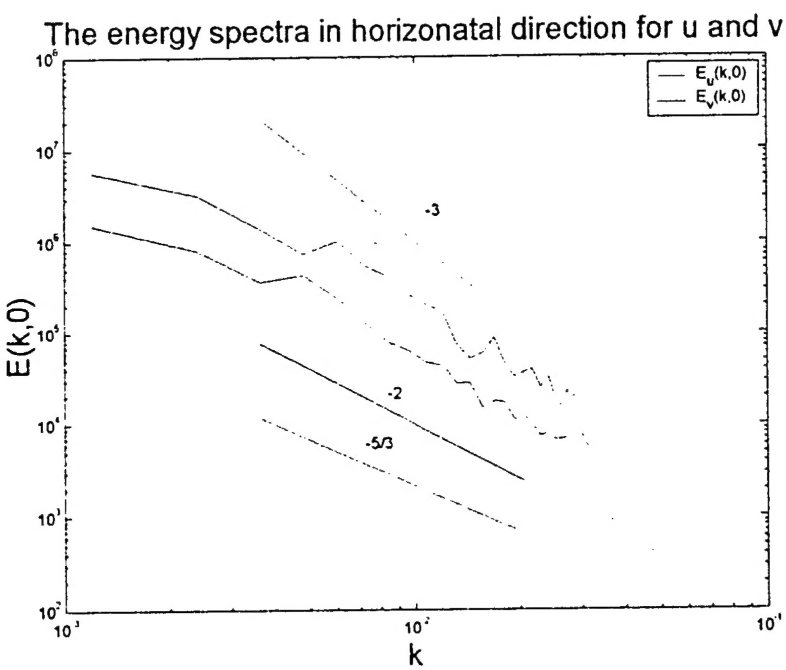

Figure 7. Velocity spectra for the non-rotating case.

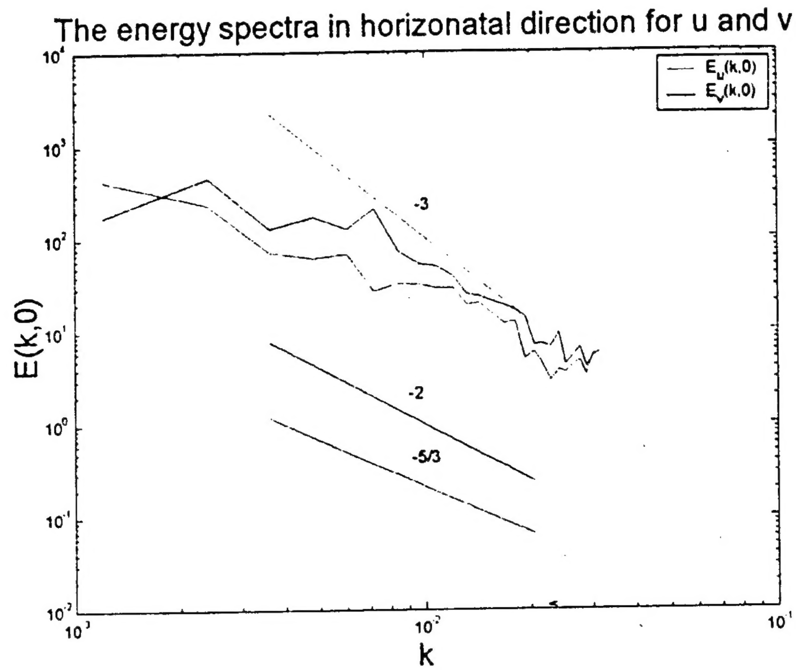

Figure 8. Velocity spectra for the case with background rotation.

The research on artificial turbulent patches was later extended to incorporate the evolution of naturally generated patches. The flow configuration of interest was a stratified shear layer, and the Kelvin Helmholtz billows generated within it was studied (this project was partially funded by the National Science Foundation). Some non-stratified experiments were also performed. It was found that the initial growth of K-H billows in non-stratified and stratified flows are similar, but their breakdown processes are dramatically different. In the non-stratified case, the breakdown to small-scale turbulence is initiated at the periphery of the billows and the turbulence generation appears as an implosive event. In the stratified case, the breakdown of the billows started explosively from the eye of the billows and small-scale instabilities and turbulence thus generated expanded outward from the eye. The measurements of r.m.s velocity fluctuations show that their behavior of stratified and non-stratified cases are also quite similar at the early stages of the K-H growth. These velocities scale well with the velocity difference across the shear layer. Striking differences, however, could be seen at later stages. The Reynolds stress measurements showed a wide variability within the shear layer. A conceptual explanation for this variability could be provided based on the dynamical structure of K-H billows in the presence and absence of stratification. Remarkable differences could be observed between the two cases, which could be attributed to the difference of evolutionary patterns noted above during the early stages of evolution.

The measurements of turbulent kinetic energy (TKE) production indicated that the K-H billowing and ensuing turbulence exchange energy with the mean flow. In regions

susceptible to the development of secondary instabilities and turbulence, typically the fluctuations absorb energy. This includes the periphery of K-H billows in non-stratified flows and the entire eye region of the stratified flows. In the stratified case, the energy fed into fluctuations decreases gradually in the downstream direction and is almost zero at a distance of one wavelength form the splitter plate where the instabilities originate. It can, therefore, be concluded that the fluctuations, which are mainly non-linear internal waves, feed energy back into the mean flow. The observations described above is consistent with the evolution of the dimensionless parameter $G=\varepsilon_o/\nu N^2$, where ν is the molecular viscosity. This parameter decreases below the critical value of about 30 beyond a distance of L. Observations show that G = 30 signifies the demise of turbulence, i.e. complete fossilization. The increase of r.m.s. velocities downstream could be attributed to the restratification following the complete fossilization. The generation of fluctuations after the demise of turbulence occurs due to the release of potential energy stored in buoyant fluid parcels that were displaced during the presence active turbulence. Once the turbulence is extinct, these fluid parcels move to their equilibrium density levels, thus releasing potential energy in the form of kinetic energy. If the resulting kinetic energy is sufficiently high such that G>30, then zombie turbulence is produced during re-stratification. The temporary increase of dissipation occurring at x ~ 1-1.5 L can be attributed to this zombie turbulence. As soon as billows are broken down to produce turbulence, ephemeral small-scale inversions appeared signifying overturning motions. Given that the flow is rapidly dissipating, this turbulence is decaying and overturning motions are also disappearing. The flow finally organizes into layered structure. At a downstream distances x > 3.5L, the growth and breakdown of K-H billows generate well defined layering which are persistent.

References:

Boyer, D.L., Davies, P.A., Fernando, H.J.S. and Zhang, X., "Linearly Stratified Flow Past a Horizontal Circular Cylinder," *Philosophical Transactions of the Royal Society (London)*, Series A, **328**, 501-528, 1989.

DeSilva, I.P.D. and Fernando, H.J.S., "Experiments on Collapsing Patches in Stratified Fluids," *Journal of Fluid Mechanics*, **358**, 29-60, 1998.

Students Supported:

John Rotter: The evolution of Kelvin-Helmholtz Billows in Non-Stratified and Stratified Shear Flows .(MS. 2000) He is currently pursuing a Ph.D. degree

Eric Pardyjak Atmospheric Boundary Layer Dynamics in Regions of Complex Terrain .(Ph.D 2001). He is currently an Assistant Professor in Mechanical Engineering at the University of Utah.